

# Coexistence of superconductivity and antiferromagnetism in single crystals $A_{0.8}Fe_{2-y}Se_2$ (A= K, Rb, Cs, Tl/K and Tl/Rb): evidence from magnetization and resistivity

R. H. Liu, X. G. Luo, M. Zhang, A. F. Wang, J. J. Ying, X. F. Wang,  
Y. J. Yan, Z. J. Xiang, P. Cheng, G. J. Ye, Z. Y. Li and X. H. Chen\*

*Hefei National Laboratory for Physical Science at Microscale and Department of Physics,  
University of Science and Technology of China, Hefei, Anhui 230026, People's Republic of China*  
(Dated: January 12, 2013)

We measure the resistivity and magnetic susceptibility in the temperature range from 5 K to 600 K for the single crystals  $AFe_{2-y}Se_2$  ( $A = K_{0.8}, Rb_{0.8}, Cs_{0.8}, Tl_{0.5}K_{0.3}$  and  $Tl_{0.4}Rb_{0.4}$ ). A sharp superconducting transition is observed in low temperature resistivity and susceptibility, and susceptibility shows 100% Meissner volume fraction for all crystals, while an antiferromagnetic transition is observed in susceptibility at Neel temperature ( $T_N$ ) as high as 500 K to 540 K depending on A. It indicates the coexistence of superconductivity and antiferromagnetism. A sharp increase in resistivity arises from the structural transition due to Fe vacancy ordering at the temperature slightly higher than  $T_N$ . Occurrence of superconductivity in an antiferromagnetic ordered state with so high  $T_N$  may suggest new physics in this type of unconventional superconductors.

PACS numbers: 74.70.Xa, 74.25.F, 74.23.Ha

One of the most amazing issues in the correlated electronic system is that there are usually the coexistence and competing of several electronic or magnetic orders. High transition temperature ( $T_c$ ) superconducting cuprates have kept being the central topics in the condensed matter physics in the past 25 years as a result of the multi-orders, which induced extremely complicated physics. Especially, the correlation between superconductivity and antiferromagnetic or spin-density-wave (SDW) order has puzzled the scientists for decades and has been thought to be related to origin of high  $T_c$  superconductivity in the cuprates. The newly discovered high- $T_c$  superconducting iron-pnictides attracted the worldwide attention immediately after the discovery of superconductivity[1–3] because the superconductivity occurs proximity to the magnetically ordered state or more than that, the coexistence of the superconductivity with antiferromagnetic order[4–6]. Naturally, one takes the iron-pnictides to compare with cuprates, and believes that they may have the same origin of high  $T_c$  superconductivity, which could be closely related to the antiferromagnetism. However, no consensus has been reached on this issue so far.

Recently, another newly discovered iron-based superconductors with  $A_xFe_{2-y}Se_2$  (A=K, Rb, Cs, Tl) with  $T_c$  around 30 K are reported [7–12]. Antiferromagnetic transition can be clearly observed in magnetization for non-superconducting Tl- or (Tl,K)-intercalated compound[12, 13]. Moun-spin rotation/relaxation ( $\mu$ SR) experiments indicate that superconductivity below  $T_c = 28$  K microscopically coexists with a magnetic ordering state with the transition temperature  $T_m = 478$  K in

$Cs_{0.8}(FeSe_{0.98})_2$ [14]. Very recently, Bao et al. reported an antiferromagnetism with Neel temperature ( $T_N$ ) as high as 559 K with the iron magnetic moment of  $3.31\mu_B$ , and a structural transition at  $T_s=578$  K due to iron vacancy ordering in superconducting  $K_{0.8}Fe_{1.6}Se_2$ [15]. Iron vacancy superstructure at  $T_s=500$  K and possible antiferromagnetic ordering with the Fe magnetic moment of  $2\mu_B$  is also reported in  $Cs_xFe_{2-y}Se_2$  ( $y=0.29$  and  $x=0.83$ )[16]. It is well known that there exists a response in resistivity to the magnetic transition, and the magnetic transition can be detected by the susceptibility in iron pnictides superconductors[17]. In order to directly study the magnetic transition and to elucidate the connection between the superconductivity and magnetic order, we study the high-temperature magnetic susceptibility and resistivity in the temperature range from 5 K to 600 K, and find the coexistence of the superconductivity and antiferromagnetism. In this letter, we report the magnetic susceptibility and resistivity from 5 K to 600 K for the  $AFe_{2-y}Se_2$  ( $A = K_{0.8}, Rb_{0.8}, Cs_{0.8}, Tl_{0.5}K_{0.3}$  and  $Tl_{0.4}Rb_{0.4}$ ). The antiferromagnetic transition was observed at  $T_N$  of  $\sim 500$ -540 K in the magnetic susceptibility for all the superconducting crystals with 100% Meissner volume fraction, indicative of the coexistence of the antiferromagnetism and superconductivity in the intercalated Iron selenides. A sharp increase in resistivity starts at the temperature slightly higher  $T_N$ . Such increase of resistivity could arise from the Fe vacancy ordering.

The single crystals were grown by Bridgeman method as reported previously[9, 10]. Resistivity below 400 K was measured using the *Quantum Design* PPMS-9. The resistivity measurement above 400 K were carried out with an alternative current resistance bridge (LR700P) by using the a Type-K Chromel-Alumel thermocouples as thermometer in a home-built vacuum resistance oven. Magnetic susceptibility was measured using the *Quan-*

\*E-mail: chenxh@ustc.edu.cn

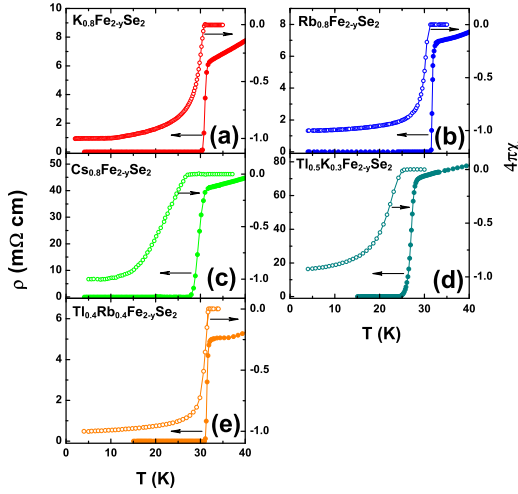


FIG. 1: (Color online) Temperature dependence of the resistivity and zero-field-cooled (ZFC) magnetic susceptibility at 10 Oe with the field applied within *ab*-plane for the superconducting  $A\text{Fe}_{2-y}\text{Se}_2$  ( $A = \text{K}_{0.8}, \text{Rb}_{0.8}, \text{Cs}_{0.8}, \text{Tl}_{0.5}\text{K}_{0.3}$  and  $\text{Tl}_{0.4}\text{Rb}_{0.4}$ ) single crystals.

tum Design SQUID-MPMS. A high-temperature oven was used in the SQUID-MPMS for magnetic susceptibility measurement above 400 K.

Five systems of superconducting  $A\text{Fe}_{2-y}\text{Se}_2$  crystals ( $A = \text{K}_{0.8}, \text{Rb}_{0.8}, \text{Cs}_{0.8}, \text{Tl}_{0.5}\text{K}_{0.3}$  and  $\text{Tl}_{0.4}\text{Rb}_{0.4}$ ) were investigated in this study. The superconducting transition temperatures ( $T_c$ ) for all the superconducting samples are listed in Table I. As shown in Fig.1, the superconducting transition width lies between 0.5 to 3 K. Especially, the transition width for  $\text{K}_{0.8}\text{Fe}_{2-y}\text{Se}_2$ ,  $\text{Rb}_{0.8}\text{Fe}_{2-y}\text{Se}_2$  and  $\text{Tl}_{0.4}\text{Rb}_{0.4}\text{Fe}_{2-y}\text{Se}_2$  is less than 1 K. The susceptibility measured in zero-field cooled process at the magnetic field of 10 Oe shows fully shielding at 5 K for the crystals with  $A = \text{K}_{0.8}, \text{Rb}_{0.8}, \text{Cs}_{0.8}$ , and  $\text{Tl}_{0.4}\text{Rb}_{0.4}$ , and 90% shielding fraction for the crystal with  $A = \text{Tl}_{0.5}\text{K}_{0.3}$ .

Figure 2 shows the temperature dependence of the resistivity in temperatures range from 5 K to 600 K for the single crystal  $A\text{Fe}_{2-y}\text{Se}_2$  with  $A = \text{K}_{0.8}, \text{Rb}_{0.8}, \text{Cs}_{0.8}, \text{Tl}_{0.5}\text{K}_{0.3}$ , and  $\text{Tl}_{0.4}\text{Rb}_{0.4}$ . All of the samples display the common features. All samples show superconducting at  $T_c$  of  $\sim 30$  K, and the  $T_c$  is listed in Table I. Resistivity shows a broad hump in the temperatures range from 70 K to 300 K ( $T_{\text{hump}}$ ) for all crystals. The magnitude of the resistivity is so high for all the samples compared to the iron-pnictide superconductors [17–19] and the FeSe single crystals[20]. Above  $T_{\text{hump}}$ , the resistivity shows a semiconductor-like behavior. A sharp increase in resistivity can be observed above 500 K for all samples, indicative of the existence of the phase transition. The temperature ( $T_S$ ), at which the resistivity starts to sharply increase, varies from 512 to 551 K with changing  $A$ . Above the  $T_S$ , the resistivity shows a weak temperature dependence. The  $T_S$  is listed in Table I for all the

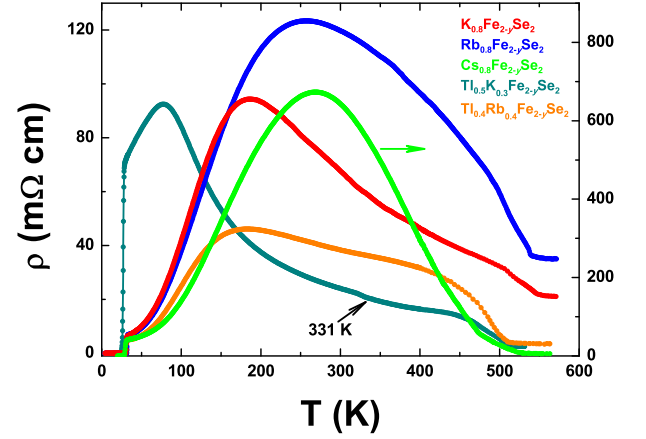


FIG. 2: (Color online) Temperature dependence of the resistivity for single crystals  $A\text{Fe}_{2-y}\text{Se}_2$  ( $A = \text{K}_{0.8}, \text{Rb}_{0.8}, \text{Cs}_{0.8}, \text{Tl}_{0.5}\text{K}_{0.3}$  and  $\text{Tl}_{0.4}\text{Rb}_{0.4}$ ). The black arrow indicates the kink in the resistivity.

samples.

In order to detect the magnetic transition and make clear what transition inferred by the kinks in the resistivity, we measured the magnetic susceptibility at 5 T in the temperature range up to 600 K, as shown in Fig. 3. A pronounced drop is observed in the magnetic susceptibility at a temperature above 500 K for all the samples. It indicates the antiferromagnetic transition at these temperatures ( $T_N$ ).  $T_N$  is 540, 534, 504, 500, and 496 K for the crystals with  $A = \text{K}_{0.8}, \text{Rb}_{0.8}, \text{Cs}_{0.8}, \text{Tl}_{0.5}\text{K}_{0.3}$  and  $\text{Tl}_{0.4}\text{Rb}_{0.4}$ , respectively. The antiferromagnetic order has been found in the  $\text{Cs}_{0.8}(\text{FeSe}_{0.98})_2$  by  $\mu\text{SR}$  with  $T_N \approx 478.5$  K[14]. And an antiferromagnetic transition has also been observed in  $\text{K}_{0.8}\text{Fe}_{1.6}\text{Se}_2$  at  $T_N$  as high as 559 K from Neutron diffraction experiments[15]. Here, magnetic susceptibility data indicate the existence of the antiferromagnetic transition above 490 K for all the crystals with  $A = \text{K}_{0.8}, \text{Rb}_{0.8}, \text{Cs}_{0.8}, \text{Tl}_{0.5}\text{K}_{0.3}$  and  $\text{Tl}_{0.4}\text{Rb}_{0.4}$ . It is worth of noting that the temperature of the kink in resistivity is slightly higher than those  $T_N$  observed in the magnetic susceptibility. Actually,  $T_N$  locates at the middle of the transition observed in the resistivity. It suggests that the sharp increase in the resistivity at high temperature is not corresponding to the antiferromagnetic transition. Indeed, the neutron diffraction results indicate that a structural transition takes place at a temperature ( $T_S$ ) just above the  $T_N$  due to the ordering of the iron vacancy,  $T_N$  and  $T_S$  are 559 K and 578 K for the sample  $\text{K}_{0.8}\text{Fe}_{1.6}\text{Se}_2$ , respectively[15]. It is easily found that the  $T_S$  corresponding to the beginning of the sharp increase in resistivity is 10-20 K higher than the  $T_N$  determined by susceptibility. Based on the observation by neutron scattering[15], we can infer that the resistivity starts to sharply increase due to the structural transition, and the kink temperature can be defined as the structural transition temperature. Therefore, we can observe the structural and antiferromagnetic transition

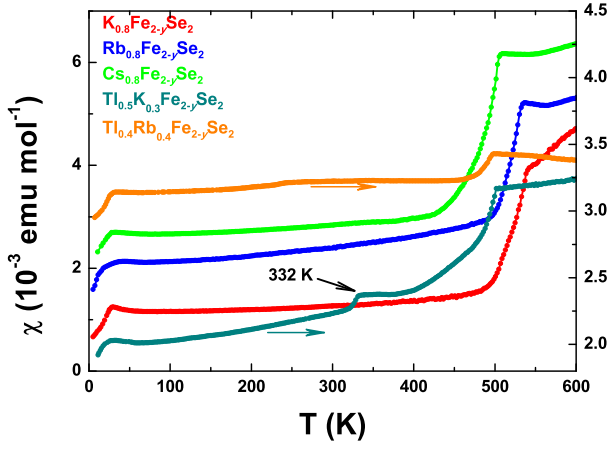


FIG. 3: (Color online) Magnetic susceptibility measured at 5 T as a function of temperature for the crystals  $A\text{Fe}_{2-y}\text{Se}_2$  ( $A = \text{K}_{0.8}, \text{Rb}_{0.8}, \text{Cs}_{0.8}, \text{Tl}_{0.5}\text{K}_{0.3}$  and  $\text{Tl}_{0.4}\text{Rb}_{0.4}$ ). The black arrow points out a kink in the susceptibility, and a similar kink is observed in resistivity.

from the resistivity and magnetic susceptibility, respectively. It should be pointed out that the  $T_N$  observed here in  $A=\text{K}$  and  $\text{Cs}$  is different from that reported by Sheradini et al.[14] and by Bao et al.[15]. It could be from different doping level although their  $T_C$  does not change so much. The black arrow in Fig.3 points out a transition at 332 K in magnetic susceptibility for the crystal  $\text{Tl}_{0.5}\text{K}_{0.3}\text{Fe}_{2-y}\text{Se}_2$ . An anomaly can also be observed in resistivity at 331 K in Fig.2. In fact, a small transition at about 250 K is also observed in susceptibility for the crystal  $\text{Tl}_{0.4}\text{Rb}_{0.4}\text{Fe}_{2-y}\text{Se}_2$ . Such behavior cannot be observed in the crystals  $A_{0.8}\text{Fe}_{2-y}\text{Se}_2$  ( $A=\text{K}, \text{Rb}, \text{Cs}$ ). Such tiny transition may be due to small amount of  $\text{Tl}_x\text{Fe}_{2-y}\text{Se}_2$  because similar transition has been observed in  $\text{Tl}_x\text{Fe}_{2-y}\text{Se}_2$  with different  $T_N$ [12, 13].

In order to carefully determine  $T_S$ , the resistivity and the corresponding derivative ( $d\rho/dT$ ) as well as the comparing with the magnetic susceptibility is plotted in Fig.4a from 400 K to 600 K for the crystal  $\text{Rb}_{0.8}\text{Fe}_{2-y}\text{Se}_2$ . A clear kink in resistivity is observed at 540 K.  $d\rho/dT$  shows two dips. One can easily find that the beginning of the high- $T$  dip in  $d\rho/dT$  corresponds to the kink in resistivity. This temperature is defined as  $T_S$ .  $T_N$  inferred from the susceptibility is 6 K less than  $T_S$ . It indicates that  $T_S$  manifests another phase transition instead of the antiferromagnetic transition observed in susceptibility. This transition should be the structural transition due to the ordering of Fe vacancies because it has been found that the structural transition occurs just before the magnetic transition[15].  $T_S$  is determined in the same way for  $A\text{Fe}_{2-y}\text{Se}_2$  with  $A = \text{K}_{0.8}, \text{Cs}_{0.8}, \text{Tl}_{0.5}\text{K}_{0.3}$  and  $\text{Tl}_{0.4}\text{Rb}_{0.4}$ , as shown Fig. 4b and Fig.4c. The obtained  $T_S$  is also listed in Table I. One can find that all  $T_S$  is slightly higher than  $T_N$  in Table I, indicating the higher transition temperature for the ordering of Fe vacancies than that of magnetic transition. Therefore, the rapid

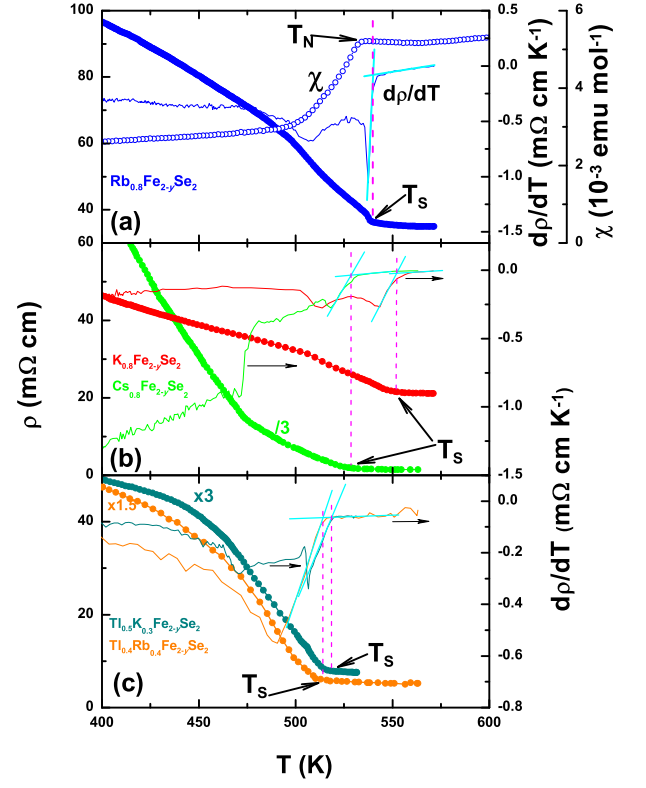


FIG. 4: (Color online) (a): Comparison of the high-temperature resistivity, its derivative and magnetic susceptibility for crystal  $\text{Rb}_{0.8}\text{Fe}_{2-y}\text{Se}_2$ .  $T_S$  inferred from the resistivity data and  $T_N$  inferred from magnetic susceptibility are shown. (b) and (c): the high-temperature resistivity and its derivative for single crystals  $A\text{Fe}_{2-y}\text{Se}_2$ : (b):  $A = \text{K}_{0.8}$  and  $\text{Cs}_{0.8}$ ; (c):  $\text{Tl}_{0.5}\text{K}_{0.3}$  and  $\text{Tl}_{0.4}\text{Rb}_{0.4}$ .  $T_S$  inferred from the resistivity is shown.

increase of the resistivity should be ascribed to arise from the Fe vacancy ordering, and consequently the very large resistivity in the normal state in the intercalated iron-selenides originates from the existence of large amount of Fe vacancies and their ordering. One can note that the  $d\rho/dT$  shows two dips for all the  $A\text{Fe}_{2-y}\text{Se}_2$  crystals except for the  $\text{Tl}_{0.4}\text{Rb}_{0.4}\text{Fe}_{2-y}\text{Se}_2$ . The dip actually manifests the change of resistivity. Therefore, the second dip can be related to the occurrence of the antiferromagnetism.

One puzzle in the intercalated iron-selenide single crystals is how to enter into superconducting state from an antiferromagnetic state with ordered Fe magnetic moment of  $3.3\mu_B$ [15] and from the high-temperature semiconductor-like behavior with very high magnitude of resistivity. One may note that resistivity increases rapidly below the structural transition temperature. It suggests that the ordering of the Fe vacancy is responsible for the semiconductor-like behavior and large magnitude of resistivity above  $T_{\text{hump}}$ . The resistivity rapidly increases from  $21.5 \text{ m}\Omega\text{cm}$  to  $94.3 \text{ m}\Omega\text{cm}$  with decreasing temperature from  $T_S$  to  $T_{\text{hump}}$  for the crys-

TABLE I: Superconducting transition temperature ( $T_c^{\text{zero}}$ ,  $T_c^{\text{onset}}$ ), the hump temperature in resistivity ( $T_{\text{hump}}$ ), antiferromagnetic transition temperature ( $T_N$ ) and structural transition temperature ( $T_S$ ) for the crystals  $A\text{Fe}_{2-y}\text{Se}_2$  ( $A = \text{K}_{0.8}$ ,  $\text{Rb}_{0.8}$ ,  $\text{Cs}_{0.8}$ ,  $\text{Tl}_{0.4}\text{K}_{0.3}$  and  $\text{Tl}_{0.4}\text{Rb}_{0.4}$ ).

sample name	$T_c^{\text{zero}}$ (K)	$T_c^{\text{onset}}$ (K)	$T_{\text{hump}}$ (K)	$T_N$ (K)	$T_S$ (K)
$\text{KFe}_{2-y}\text{Se}_2$	—	—	—	527	540
$\text{K}_{0.8}\text{Fe}_{2-y}\text{Se}_2$	30.5	31.5	170	540	551
$\text{Rb}_{0.8}\text{Fe}_{2-y}\text{Se}_2$	31.5	32.0	250	534	540
$\text{Cs}_{0.8}\text{Fe}_{2-y}\text{Se}_2$	27.5	30.9	270	504	525
$\text{Tl}_{0.4}\text{K}_{0.3}\text{Fe}_{2-y}\text{Se}_2$	24.8	27.7	78	496	515
$\text{Tl}_{0.4}\text{Rb}_{0.4}\text{Fe}_{2-y}\text{Se}_2$	30.9	31.8	180	500	512

tal  $A_{0.8}\text{Fe}_{2-y}\text{Se}_2$ . It indicates that the Fe vacancy ordering makes the carrier localized and strongly scatters the charges. Usually, the antiferromagnetic spin-density-wave transition in the iron-pnictides has been thought to be related to the reconstruction of Fermi surface (RFS). Such RFS can induce a more metallic resistivity (like in  $\text{BaFe}_2\text{As}_2$  and  $\text{LnOFeAs}$  systems). One possible origin of the metallic resistivity below  $T_{\text{hump}}$  can be the joint result of the ordering of the Fe vacancies and the occurrence of antiferromagnetism. All of these mysteries require further experimental and theoretical study.

The above results indicate that the superconductivity in the  $A_x\text{Fe}_{2-y}\text{Se}_2$  happens in an antiferromagnetic ordering state with very high transition temperature  $T_N$ . In order to understand the coexistence of the superconductivity and antiferromagnetic order with very high  $T_N$ , we measured resistivity and susceptibility on non-superconducting crystal  $\text{KFe}_{2-y}\text{Se}_2$  (The data are not shown here). Although this sample is not superconducting and shows a semiconducting behavior in the whole temperature range, resistivity and magnetic susceptibility display the similar behavior at high temperatures as those of the superconducting samples. An antiferromagnetic transition with  $T_N = 527$  K is observed in susceptibility. Surprisingly, the  $T_N$  is lower than that in the superconducting  $\text{K}_{0.8}\text{Fe}_{2-y}\text{Se}_2$  crystal. Resistivity shows a transition at 540 K due to iron vacancy ordering. Both  $T_N$  and  $T_S$  are higher in the superconducting sample  $\text{K}_{0.8}\text{Fe}_{2-y}\text{Se}_2$  than the non-superconducting sample. It implies that the coexistence of the antiferromagnetic

ordering and the superconductivity is not simply competing. It requires to clarify how superconductivity occurs in such antiferromagnetic ordered state.

In summary, we first report the magnetic susceptibility and resistivity from 5 K to 600 K for the crystals  $A\text{Fe}_{2-y}\text{Se}_2$  ( $A = \text{K}_{0.8}$ ,  $\text{Rb}_{0.8}$ ,  $\text{Cs}_{0.8}$ ,  $\text{Tl}_{0.5}\text{K}_{0.3}$  and  $\text{Tl}_{0.4}\text{Rb}_{0.4}$ ). The structural and antiferromagnetic transition temperatures are systematically determined by resistivity and susceptibility for all the superconducting crystals with 100% Meissner volume fraction, indicative of the coexistence of the antiferromagnetism and superconductivity in the intercalated iron selenides. A sharp increase in resistivity starts at the  $T_S$  slightly higher than  $T_N$ . Such increase of resistivity could arise from the Fe vacancy ordering. The higher  $T_N$  and  $T_S$  in the superconducting crystal relative to non-superconducting crystal suggests that antiferromagnetic magnetism and superconductivity are not simply competing to each other. Occurrence of superconductivity in an antiferromagnetic ordered state with so high  $T_N$  and the large magnetic moment of Fe up to  $3.3\mu_B$  may suggest new physics in this type of unconventional superconductor.

**ACKNOWLEDGEMENT:** X. H. Chen would like to thank W. Bao for useful discussion. This work is supported by the Natural Science Foundation of China and by the Ministry of Science and Technology of China, and by Chinese Academy of Sciences.

- 
- [1] Y. Kamihara, T. Watanabe, M. Hirano, and H. Hosono, J. Am. Chem. Soc. **130**, 3296 (2008).
  - [2] X. H. Chen, T. Wu, G. Wu, R. H. Liu, H. Chen, and D. F. Fang, Nature **354**, 761 (2008).
  - [3] Z. A. Ren et al., Chinese Phys. Lett. **25**, 2215(2008).
  - [4] R. H. Liu, G. Wu, T. Wu, D. F. Fang, H. Chen, S. Y. Li, K. Liu, Y. L. Xie, X. F. Wang, R. L. Yang, L. Ding, C. He, D. L. Feng, and X. H. Chen, Phys. Rev. Lett. **101**, 087001 (2008).
  - [5] H. Chen, Y. Ren, Y. Qiu, Wei Bao, R. H. Liu, G. Wu, T. Wu, Y. L. Xie, X. F. Wang, Q. Huang and X. H. Chen, Europhys. Lett. **85**, 17006(2009).
  - [6] A. J. Drew, Ch. Niedermayer, P. J. Baker, F. L. Pratt, S. J. Blundell, T. Lancaster, R. H. Liu, G. Wu, X. H. Chen, I. Watanabe Nature Materials **8**, 310 (2009).
  - [7] J. Guo, S. Jin, G. Wang, S. Wang, K. Zhu, T. Zhou, M. He and X. Chen, Phys. Rev. B **82**, 180520 (2010).
  - [8] Yoshikazu Mizuguchi, Hiroyuki Takeya, Yasuna Kawasaki, Toshinori Ozaki, Shunsuke Tsuda, Takahide Yamaguchi and Yoshihiko Takano, arXiv:1012.4950 (unpublished).
  - [9] A. F. Wang, J. J. Ying, Y. J. Yan, R. H. Liu, X. G. Luo, Z. Y. Li, X. F. Wang, M. Zhang, G. J. Ye, P. Cheng, Z. J. Xiang, X. H. Chen, arXiv:1012.5525 (unpublished).

- [10] J. J. Ying, X. F. Wang, X. G. Luo, A. F. Wang, M. Zhang, Y. J. Yan, Z. J. Xiang, R. H. Liu, P. Cheng, G. J. Ye, X. H. Chen , arXiv:1012.5552 (unpublished).
- [11] A. Krzton-Maziopa, Z. Shermadini, E. Pomjakushina, V. Pomjakushin, M. Bendele, A. Amato, R. Khasanov, H. Luetkens and K. Conder, arXiv:1012.3637 (unpublished).
- [12] Minghu Fang, Hangdong Wang, Chiheng Dong, Zujian Li, Chunmu Feng, Jian Chen, H.Q. Yuan, arXiv:1012.5236 (unpublished).
- [13] J. J. Ying, A. F. Wang, Z. J. Xiang, X. G. Luo, R. H. Liu, X. F. Wang, Y. J. Yan, M. Zhang, G. J. Ye, P. Cheng and X. H. Chen, arXiv: 1012.2929 (unpublished).
- [14] Z. Shermadini et al., arXiv:1101.1873 (unpublished).
- [15] W. Bao et al., arXiv:1102.0830 (unpublished).
- [16] V. Yu. Pomjakushin et al., arXiv:1102.1919 (unpublished).
- [17] X. F. Wang et al., Phys. Rev. Lett. **102**,117005(2009).
- [18] X. F. Wang, T. Wu, G. Wu, R. H. Liu, H. Chen, Y. L. Xie, and X. H. Chen, New Journal of Physics **11**, 045003 (2009).
- [19] P. Cheng, H. Yang, Y. Jia, L. Fang, X. Y. Zhu, G. Mu, and H. H. Wen, Phys. Rev. B **78**, 134508 (2008).
- [20] D. Braithwaite, B. Salce1, G. Lapertot, F. Bourdarot, C. Marin, D. Aoki, and M. Hanfland, J. Phys.: Condens. Matter **21**, 232202 (2009).